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SOIL TEMPERATURE CONDITIONS ON A CENTRAL ALPINE SLOPE ON BOTH SIDES OF THE TIMBERLINE

PART III: SOIL TEMPERATURE IN RELATIONSHIP TO OTHER CLIMATIC FACTORS

Herbert Aulitsky

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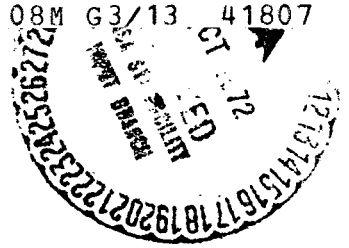

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SOIL TEMPERATURE CONDITIONS ON A CENTRAL ALPINE SLOPE ON BOTH SIDES OF THE TIMBERLINE

PART III: SOIL TEMPERATURE IN RELATIONSHIP TO OTHER CLIMATIC FACTORS

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ABSTRACT: The correlation between soil surface temperature and soil temperature and other climatic elements, and the differences of these correlations between mountainous and plain regions are investigated. With equal duration of sunshine, the amplitudes of surface temperature variations are greater at high altitude. The same holds for the relation between surface temperature and cloudiness.

The relation between air temperature and soil temperature shows great local variations. At a location with a snow cover, the soil temperature remains above the air temperature during the winter months. During summer, the upper layers of the soil are mostly warmer than the air. This effect is greater at locations with good ventilation because of reduced heating of the air from below, and smaller in thin forest with less ventilation. In dense cembra pine forest air and soil surface temperatures are nearly equal.

The formation of dew may raise the surface temperature by several degrees C.

1. The Influence of Sunshine Duration

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A relatively large percentage of effective sunshine duration which would naturally influence the soil temperature was found by Steinhauser [1] in the inner Alpine continental region and especially in the area of the Oetztal Alps. In addition, Turner [2] pointed out that in the high mountains the total radiation under cloudy skies exceeds the usual intensity measured at lower levels (see also [4]), where the stronger horizontal screening of the high-altitude stations is compensated in particular. Since even in cloudless skies the solar radiation is stronger than on the plains and since on the other hand the relatively low air temperatures at night influence the soil temperature conditions, larger daily amplitudes of surface temperature result than on the plains.

*Numbers in the margin indicate pagination in the foreign text.

From the records of the soil surface temperatures at the base station at treeline (I) and the recordings of the sunshine duration for the time from June 1 1954 to November 30 1955 a relatively clear relationship was found between daily amplitudes of soil temperature (0 to 1 cm depth) and the sunshine duration (Table 1). With increasing sunshine duration the daily amplitude of soil temperature increased at a somewhat higher rate, for instance, in the Vienna values (lawns in the Garden of the Central Institute for Meteorology). While the cleared base observation point (I) at Obergurgl, for instance, showed for a sunshine duration of 10 to 12 hours in June an average daily amplitude of the soil surface of 32.6°C, Vienna showed only 25.3°C [3]. If we consider the vegetation-covered observation point at Obergurgl we could for instance diminish this amplitude difference of 7.4°C to approximately 2.6°C. An increase of the soil surface amplitude resulting from elevation above sea level remains measurable even though it is no longer particularly large.

Table 1 contains several deviations which were likely caused by the small number of observations or were caused by the snow cover persisting into May.

TABLE 1. DAILY AMPLITUDE OF THE SOIL TEMPERATURE (0 TO 1 CM) OF THE HORIZONTAL CLEARING (I) AS A FUNCTION OF SUNSHINE DURATION, °C. (MEASUREMENTS OF 2 VEGETATION PERIODS, 1954 TO 1955)

Sunshine Duration	May[2]	June	July	Aug.	Sept.	Oct.	Nov.[1]
0 - 2 hours	14.0	17.4	14.0	15.8	13.2	10.5	2.9
2 - 4 hours	11.6	23.0	21.2	18.8	20.2	7.7	2.6
4 - 6 hours	16.5	25.6	23.6	23.4	24.7	11.2	3.0
6 - 8 hours	----	26.9	27.7	25.0	26. 0	21.1	---
8 - 10 hours	25.2	29.9	28.6	29.7	28.1	----	---
10 - 12 hours	19.8	32.6	31.1	29.5	----	----	---

2. The Influence of Cloud Cover

The recordings of the Obergurgl-Poschach/tree line (I) for the period of June 1954 to November 1955 were also used to establish the base station relationship between the degree of cloud cover and soil surface temperature,

[1] Only in 1954.
[2] Only from May 14 to May 31., 1955.

but considering only the time without snow. Larger daily amplitudes of the soil temperature (Table 2) also resulted here, as for instance in Vienna [3], but the different cultivation situations of the two observation points must be taken into account. Considering again the vegetation-covered observation point at Obergurgl, the difference between the Obergurgl and Vienna amplitudes diminishes to approximately 1/3 of the measured value. It should be pointed out, however, that particularly for high cloudiness conditions the Vienna values are far below the Obergurgl values, showing the stronger significance of diffuse irradiation in high-altitude locations.

TABLE 2. DAILY AMPLITUDE OF THE SOIL TEMPERATURE (0 TO 1 CM) AS A FUNCTION OF THE CLOUD COVER ON THE HORIZONTAL CLEARING (I) (1955 AND 1955)

Cloudiness	May[2]	June	July	Aug.	Sept.	Oct.	Nov.[1]
0 - 3 (clear)	19.4	30.3	31.9	28.5	28.3	16.4	2.8
4 - 7 (cloudy)	17.7	26.0	26.5	23.0	23.0	13.0	3.0
8 - 10 (overcast)	14.5	21.0	18.7	18.6	18.6	10.7	2.9

(4")

3. The Relationship of Soil Surface and Soil Temperature to Air Temperature

Since the air temperature in the mountains is significantly more frequently measured than the soil temperature, a clear relationship between the above-mentioned values would allow estimation of the biologically often interesting soil temperature values where no personal measurements exist. On the basis of our own substantial data on air and soil temperature measurements the question should be asked of how practically useful and regular functions can be measured.

In the foreground of the observation we again have the situation of the stations covered with snow in winter, which applies to the substantial majority of sub-alpine levels. We should, however, allow for small position-dependent deviations from this climatological normal case, since, as we know, the air temperatures at a particular altitude will differ only slightly, while on the other hand the soil and especially the soil surface

[1]Only in 1954.
[2]Only from May 14 to May 31, 1955.

temperatures will show large position-dependent differences.

Based on the monthly averages, extremes and amplitudes of soil surface temperatures from 0 to 1 cm depth and of the air temperatures at the 200-cm level (at the snow-covered base station Obergurgl/Poschach-tree-line [I] [2072 m]) a relatively clear relationship exists between soil surface and air temperatures (Figure 1). During the vegetative period the monthly average and extreme values of the soil surface temperature are always higher than the corresponding air temperature values. Exceptions occur principally in the early spring or late fall: in the spring the soil at relatively high air temperatures has not yet warmed up under the snow cover, and in the fall, with a low sun, the soil cooling becomes noticeable. Quite characteristic of the observations of snow-covered locations is the strong bending of the curve in the 0°C range: because of the snow cover the low winter air temperatures are not able to penetrate the soil; regardless of the deviations of the air temperature, the temperature remains constant; immediately after the thaw, however, the soil surface temperatures begin to increase rapidly and exceed by far the corresponding air temperature values. The bend corresponds to the different conditions in summer and winter. /367

Since the absolute extremes are always the result of a particular climatic situation this relationship (dashed line in Figure 1) deviates predictably from the average value (solid line). The strong dependence of the soil surface temperature on insolation is expressed in the relationship of the amplitudes, where approximately equal air temperature amplitudes will correspond to different soil surface temperature amplitudes.

If we compare, instead of the soil surface temperatures, the soil temperatures at the root level (10 cm) with the air temperatures we would come closer to the values during the summer period (Table 3 and thin dashed curve in Figure 1): at this soil depth the average and median extremes are no longer as high above the air temperature values as during the summer half-year period at the surface level immediately influenced by radiation (Table 3). The largest differences between air and soil temperature at

10-cm depth occur in the fall when the air cools faster than the ground, and also in the spring, when the air warms up faster than the still snow-covered ground (change of direction of the curve). The influence of the winter snow cover naturally creates the characteristic bending of the curve; the same factor is also responsible for the relatively small number of frost and ice days as well as the frost exchange in the ground (Table 4).

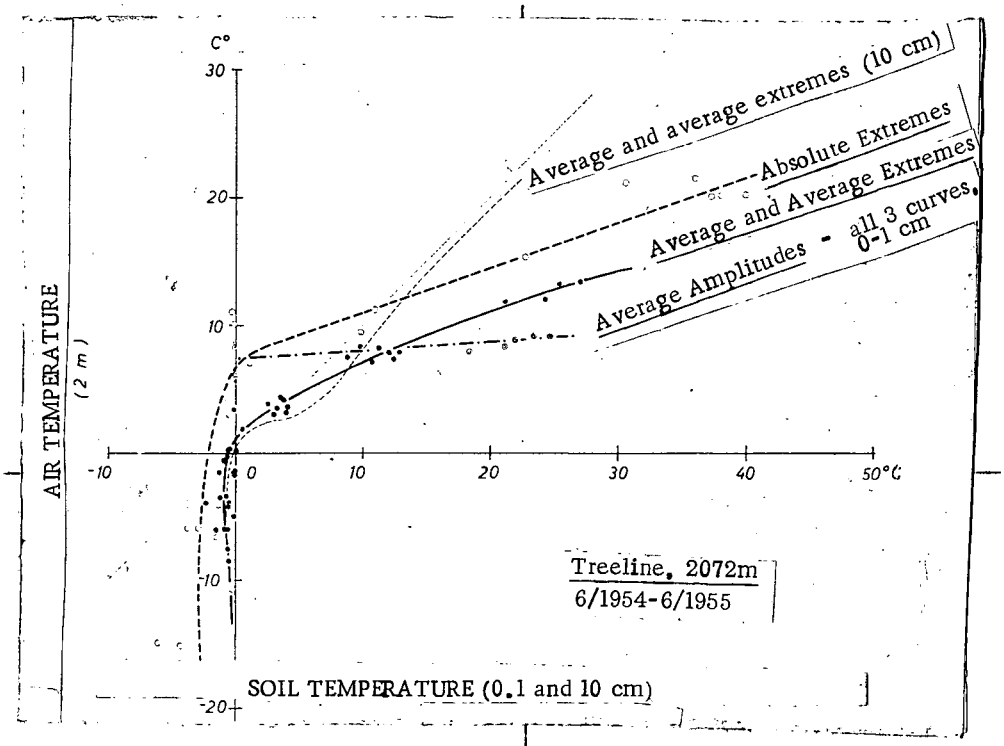

Figure 1. Relationships between Soil Surface and Soil Temperature (0 to 1 and 10 cm) on the One Hand and the Air Temperature on the Other at Obergurgl/Poschach Treeline Station (I), 2072 m, June 1954-June 1955.

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TABLE 3. MONTHLY AVERAGE VALUES OF AIR TEMPERATURE AND SOIL TEMPERATURE AT 0 TO 1 CM AND AT 10 CM DEPTH OF THE HORIZONTAL CLEARING (I), 2072m, °C.

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	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept	Oct.	Nov.	Dec.
1954:												
Air, 200 cm	-----	---	---	---	---	7.9	7.1	8.2	7.5	3.2	1.5	3.6
Ground, 0 - 1 cm	---	---	---	---	---	12.0	10.6	11.2	8.7	2.9	1.3	1.2
Ground, 10 cm	---	---	---	---	---	---	10.7	11.4	9.5	3.6	0.2	0.8
1955:												
Air, 200 cm	3.4	7.6	4.9	1.6	3.0	7.3	9.2	8.0	6.1	1.6	1.8	---
Ground, 0 - 1 cm	0.7	0.6	0.5	0.1	3.0	12.3	14.0	12.1	9.0	2.0	0.2	---
Ground, 10 cm	0.4	0.4	0.3	0.0	2.0	11.3	13.4	11.5	9.0	3.5	0.5	---

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TABLE 4. NUMBER OF FROST DAYS AND FROST CHANGES, 200 CM ABOVE THE SOIL AND 0 TO 1 CM, AND 10 CM DEEP IN THE SOIL OF THE HORIZONTAL CLEARING (I, 2072m).

(4)

	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Number of frost changes:												
Air, 200 cm 1954	---	---	---	---	---	2	4	0	5	12	23	30
Ground, 0-1 cm 1954	---	---	---	---	---	2	0	0	3	21	28	31
Ground, 10 cm 1954	---	---	---	---	---	0	0	0	0	0	15	31
Air, 200 cm 1955	31	28	27	25	21	6	0	2	7	17	22	--
Ground, 0-1 cm 1955	31	28	31	31	10	1	0	0	8	26	25	--
Ground, 10 cm 1955	31	28	31	2	1	0	0	0	0	2	0	--
Number of frost changes:												
Air, 200 cm 1954	---	---	---	---	---	6	6	0	13	36	44	39
1955	62	8	28	55	44	18	0	4	15	29	35	--
Ground, 0-1 cm 1954	---	---	---	---	---	4	0	0	8	44	13	0
1955	0	0	0	0	17	2	0	0	17	40	20	--
Ground, 10 cm 1954	---	---	---	---	---	0	0	0	0	0	1	0
1955	0	0	0	0	13	0	0	0	0	0	--	--

During the processing of the data from the base station (I) it emerged that contrary to expectations the minimum values for soil surface (0 to 1 cm) were relatively frequently above the air temperatures at an elevation of

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2 cm. Since instrument errors could be excluded as a cause because of the repeated calibrations and therefore must be due to the known data from other stations, a selection of minimum values as a function of the degree of cloud cover was performed. This showed that the soil surface temperature minima were clearly below the corresponding air temperature values even for low degrees of cloud cover (0 to 2), while with greater cloudiness they were frequently above the simultaneously measured air temperatures (Figure 2). This phenomenon can be explained in most instances only by the aftereffect of the preceding daily warming of the site itself, in less frequent cases by the insulating effect of a snow cover and by the heat of condensation created by dew formation and fits the pattern of a "warm hanging zone" [5]. The average monthly minima at the soil surface, however, were regularly below the corresponding air temperature values during the vegetative period (Table 5).

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The comparison of air and soil temperatures of the base station, which is snow-covered in winter, has consequently supported the observations of Schubert [6] and Maurer [7], stating that with increasing elevation above sea level the excess of the soil temperature yearly average above the air temperature yearly average increases as a consequence of the snow cover (Table 4 and 10 [8]). If in comparison with the data of those authors we were to eliminate the influence of different elevations and measurement depths, the excesses of our own soil temperature yearly averages would become somewhat smaller but would nonetheless confirm the fundamental facts.

TABLE 5. DIFFERENCES OF THE AVERAGE MONTHLY MINIMA AT 200 CM ABOVE GROUND AND 0 TO 1 CM IN THE GROUND OF THE HORIZONTAL CLEARING (I, 2072 m).

Year	Jan.	Feb.	Mar.	April.	May	June	July	August	Sept.	Oct.	Nov.	Dec.
1954	---	---	---	---	---	+0.5	+0.3	+0.9	+1.4	+0.8	-1.5	-4.5
1955	-5.3	-9.6	-8.0	-4.9	-11.3	-0.4	-0.1	+0.6	+1.3	+0.7	-3.5	---

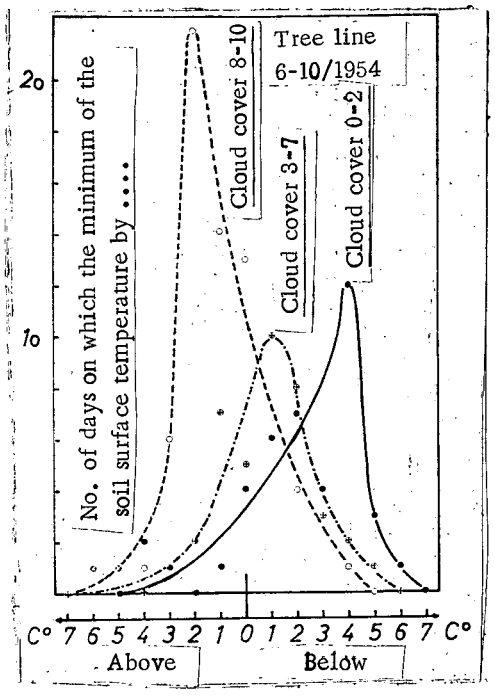
Tree line
6-10/1954
Cloud cover 8-10
Cloud cover 3-7
Cloud cover 0-2
No. of days on which the minimum of the soil surface temperature by ....
20
10
C° 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 C°
Above
Below

Figure 2. Frequency distribution of the deviations of air temperatures from the daily minima of soil surface (0 to 1 cm) of the base station at the tree line (II), 2072 m, from June through October, 1954 for different degrees of cloud cover.

The regularities introduced are only valid for the base station (snow-covered in winter) and it is interesting to find out how gradual deviations of these relationships may occur at other locations. In snow-free, wind-exposed and shady locations the ground temperatures in summer as well winter will come much closer to the air than for the base station under strong radiation influence. The lower irradiation tends to diminish the occurrence of higher maximum values even here at the surface; the ground warming remains so low that the average remains below that of the air temperature and even in the winter the ground and air temperature values remain very similar because of a lack of snow cover (Tables 1, 16, 17 and 18 in [8]).

At overheated points, however, the summer soil temperature values exceed the local air temperature values by a still larger amount than at the base station (I).

The extraordinarily strong radiation and ventilation dependence of the difference of ground and air temperatures for approximately constant air temperatures leads to the expectation of a particular local multiplicity, resulting in overly large radiation and ventilation differences resulting from forest and ground vegetation. This naturally applies principally to the sub-Alpine cembra-pine forest and has led to our particularly detailed investigation of the correlations of thermal factors.

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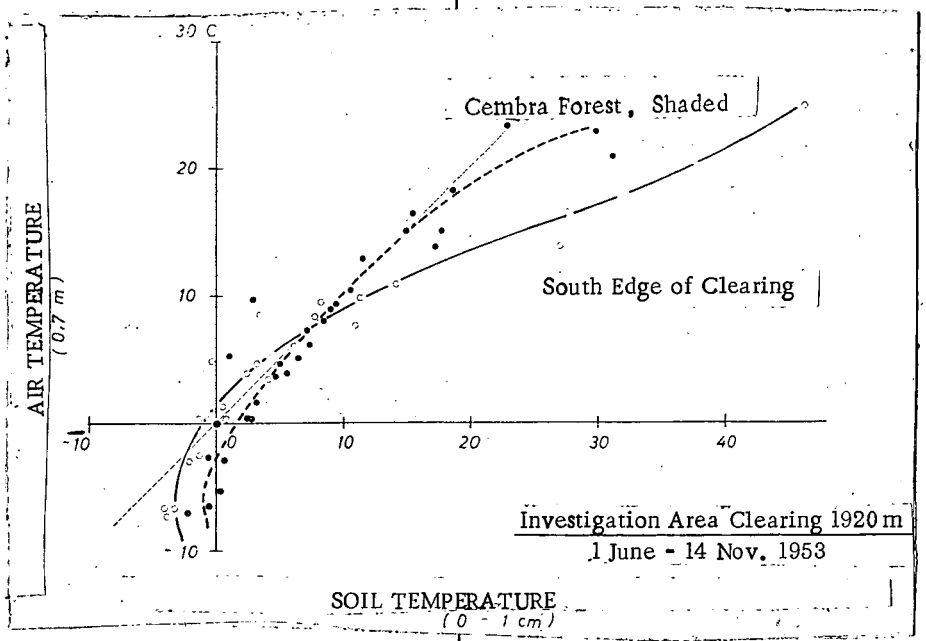

Figure 3. Relationships Between Soil Surface Temperature (0 to 1 cm) and Air Temperature at 70 cm at Measurement Points in Cembra Forest (Shaded, 1a) and at the South Edge of the Clearing (6d). The curves were plotted with the aid of the monthly average and the average and absolute extremes. (4'')

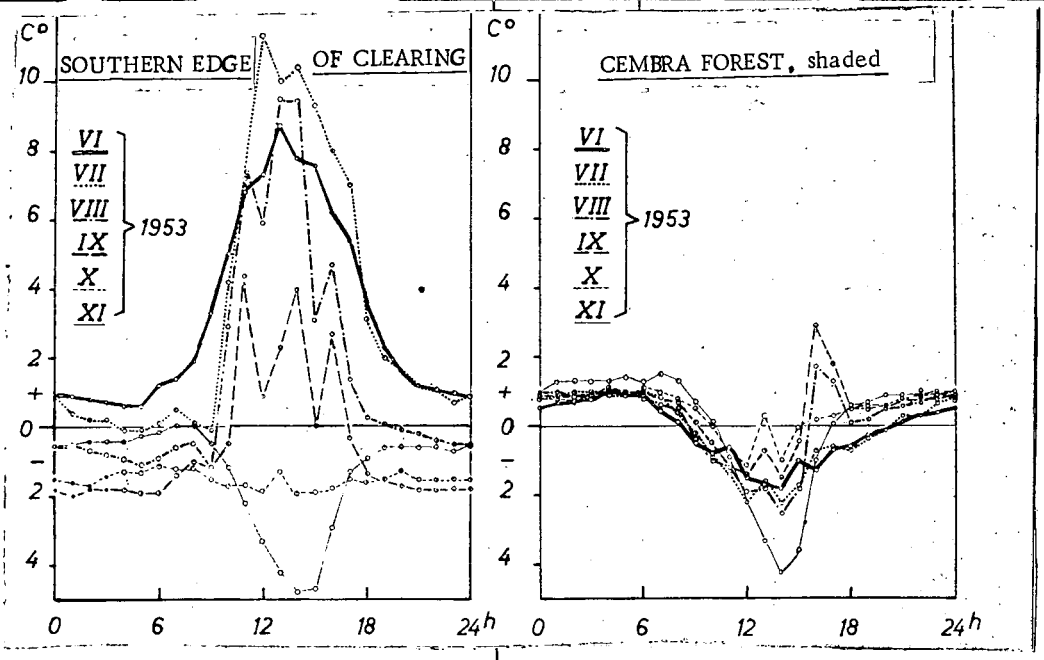

Figure 4. Daily Course of the Average Monthly Temperature Differences Between Soil Surface (0 to 1 cm) and the Observation Shed (70 cm above ground) at the Observation Location at the Southern Edge Clearing (6d) and the Shaded Cembra Forest (1a) From June 1 to November 14, 1953.

With the intention of demonstrating the differences, a clearing station (southern edge, 6d) was compared to the strongly shaded cembra forest station (Figures 3 and 4). The radiation and ventilation influenced station in the clearing yielded a similar ratio as we know from the base (I). The forest station in the vicinity of the observation post has led to a somewhat stronger air warming relative to the conditions at the tree line, since there the locally warmed air can remain longer as a ground-hugging air layer during the periodic wind system. In the cembra forest, however, the soil temperature was only slightly influenced by direct sunshine and ventilation, so that the air and soil surface temperatures are substantially more similar (the curve in Figure 3 approximates, except for the lower and higher ranges, the 45° line).

The correlation between air and soil temperatures is not only subject to radiation-caused local differences; we can also determine a distinctive and location-dependent daily course which changes again with the seasons /372
(Figures 4 and 5). At a radiation-influenced observation point (for instance, the southern edge of the clearing, 6d) the soil temperature (4'') remains substantially above the simultaneous air temperature for days (Figure 4). Only in late summer and fall do these differences diminish under the influence of increasingly longer tree shadows (dashed and dotted curves, Figure 4), creating in October a condition characterized by strong shadows and high reflection of a diminishing sunshine (thinly dashed line); the soil temperature remains below the air temperature during the whole day. Finally in November the snow cover impedes all daily changes of the soil surface temperature while the air temperature still changes and consequently leads to a reversal of the relationships (thin solid curve of Figure 4). The strong radiation dependence of the difference of the two temperatures is shown by Figure 5 which shows that both a sunny forest observation location and a sunny clearing location result in similar relationships (Curve 4 in Figure 5) and that a shady clearing observation point (Curves 2, 3, 5) shows the same relationships as in the forest. Unmistakably the forest climate manifests itself in the summer months in the shady cembra forest (1a), when because of the

reflection protection by the crowns the soil surface temperatures at night are higher than the simultaneous air temperatures (Figure 4, right), but because of the lack of direct sunshine the air temperatures are no longer reached for days.

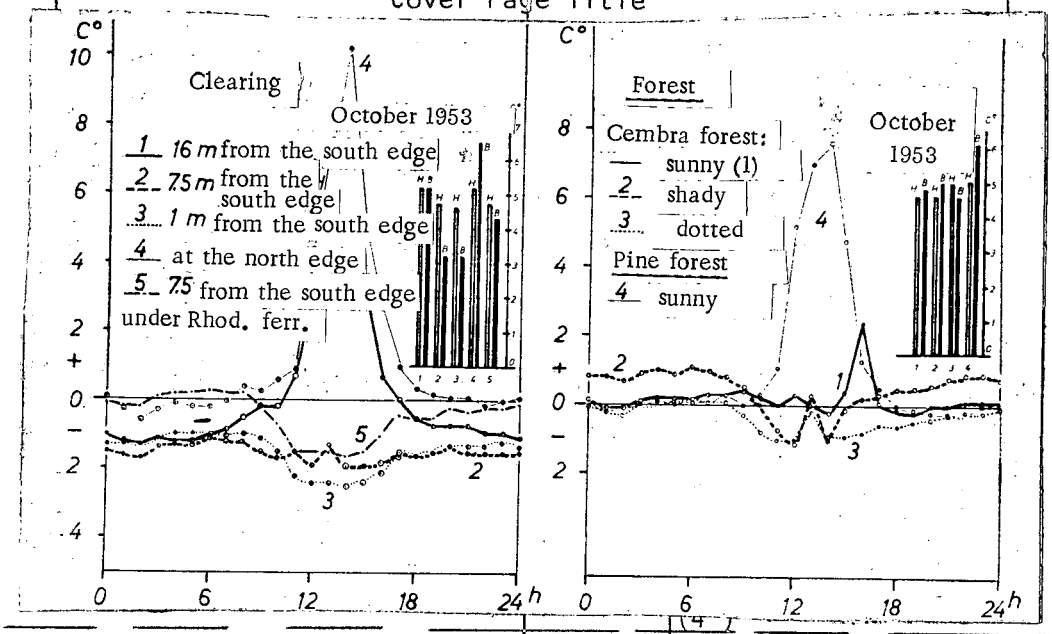

Figure 5. Daily Course of the Average Monthly Temperature Differences Between Soil Surfaces (0 to 1 cm) and the Observation Shed (70 cm above ground) at Clearing and Forest Stations Under Different Sunshine Conditions (7d, 6d, 6a, 8a, 6e, 1d, 1a, 3a, 2a) in October 1953.

The examples introduced allow for a particular multiplicity in the correlations between air and soil temperatures which can be clearly explained as a result of the influences of maintenance of radiation, growth and finally ventilation and apparently result in the following irregularity: at a strongly radiation-influenced observation point the soil surface temperatures, like the upper soil layers not subject to very strong ventilation, are above the air temperatures (as, for instance, the observation points "aisle", 5a, "central clearing", 7a, d,"north edge-clearing", 8a and "pine forests", 2a even in fall, as Figure 6 shows). Observation points with less radiation are characterized by the fact the surface temperature average is still above the air temperature but the soil temperatures, because of the surface warming, are below the air temperatures; we include for instance the cembra forest station (1a) and

the observation point at the south edge of the clearing (6d), in the summer period. For minimum direct sunshine the surface and soil temperature averages remain below the corresponding air temperature values; examples of this are the horst stations (4a) in the summer period and the observation point at the south edge of the clearing (6d) and the pine-cembra forest (3a) in the fall. With a lower sun position and increasing shadows certain observation points change their form; in Figure 6 we can introduce as examples the observation points at the south edge and at the center of the clearing. Particularly striking relationships are shown by the triangular representations for the horst stations where because of strong local shading of the observation point and simultaneous influencing of the air temperature by the neighboring clearing and aisle, larger differences result the average values in (Figure 6).

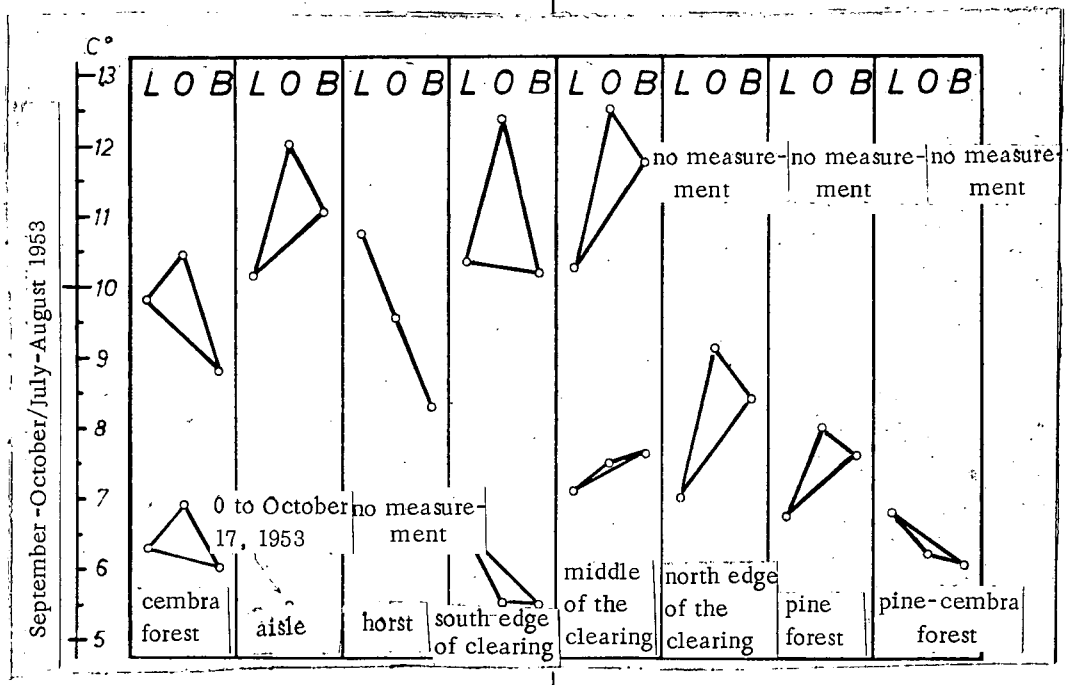

Figure 6. Average Values of the Air Temperature In the Observation Shed At 70 cm Height Above Ground (L), of the Soil Surface Temperature (O) In 0 to 1 cm Depth and of the Soil Temperature (B) At 10 cm Depth In July-August 1953 and September-October 1953 (Observation points 1a, 5a, 4a, 6d, 7a, d, 8a, 2a, 3a). NASA

It was intentionally that the particular triangular representation (Figure 6) was selected which had been used by H. Pallmann and E. Frei [9] for differentiating their "effective average temperatures" to indicate that the position of the actual arithmetic mean leads only to small differences between the upper and the subsoil observation points but which nonetheless characterizes the ecological relationships and allows for a climatological comparison. These small differences can be attributed to the sensitivity of the instrumentation.

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4. The Effect of Dew

While the soil temperature suddenly decreases through penetration of rain precipitation [5] or a cloudburst [10], because of the resulting freed condensation heat dew formation often leads to not insignificant temperature increases in the range of soil surfaces. A comparative observation of soil temperature measurements during the year 1953 showed that his process can be verified particularly in the fall months (Table 6), as was already indicated by G. Hofmann [11].

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TABLE 6. INCREASE OF THE SOIL SURFACE TEMPERATURE (0 to 1 cm) AS A RESULT OF FREED CONDENSATION HEAT. INVESTIGATION AREA CLEARING-POSCHACH, VEGETATION PERIOD 1953.

Date	Time	Open area without vegetation (6d)	Open area with vegetation	Cembra forest (1d)	Relative air humidity (%) 70 cm
11 July	24^{30}	0.4	--	--	92%
13 July	20^{30}	0.3 - 0.4	--	0.1	92%
1 August	20^{45}	0.2	--	--	94%
4 Sept.	21^{00}	0.5	0.3	0.1	96%
5 Sept.	0^{00}	1.2 - 1.5	1.2	0.6	100%
	22^{00}	1.0 - 2.8	2.0	1.1	99%
6 Sept.	55^{00}	7.7(?) - 4.3	4.4	3.1	99%
1.Oct.	20^{15}	0,5 - 1.0	0.4	0.3	99%
23 Oct.	21^{00}	0.5 - 0.9	0.7	0.4	90%

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As an example, we can use the period of September 4 to 6 1953. These were days of a fall period of good weather characterized by a well-established periodic wind system and high night air moisture. Figure 7 contains the effective measurements at the south edge points (shady edge, observation point 6d) and shows the daily total radiation and soil surface temperature (0 to 1 cm) caused by the traveling tree shadows. The long-wave reflection and the radiation balance could no longer be followed so that a comparison with air temperature and relative humidity (observation shed 70 cm above ground) can no longer be correlated to cloud cover and total radiation.

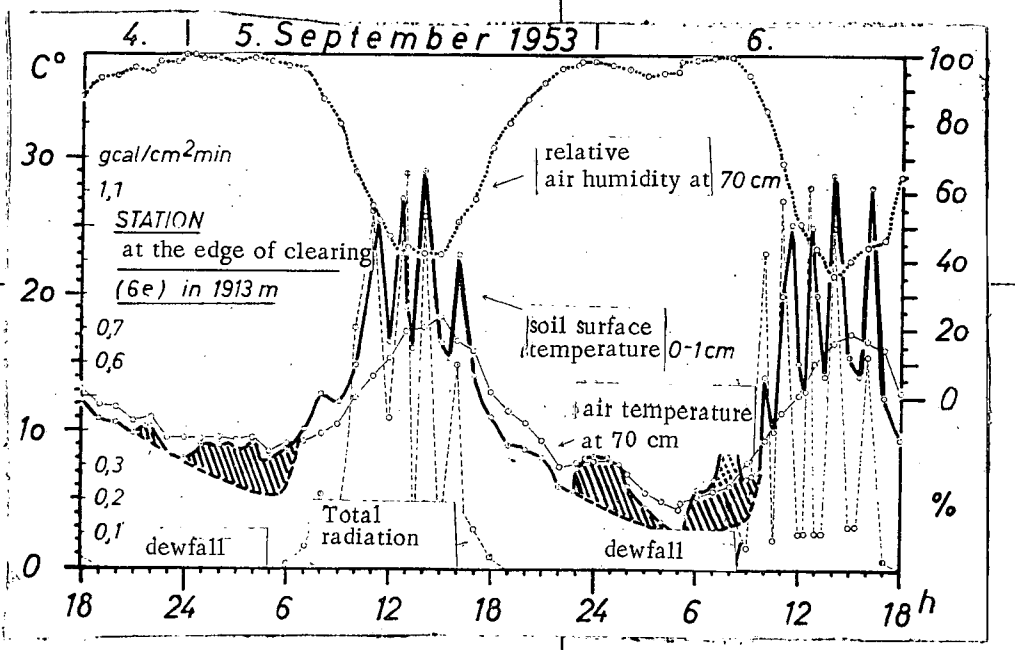

Figure 7. Increase of the Soil Surface Temperature Resulting From Dew Formation In the Night of September 4th to 5th and September 5th to 6th 1953 At Observation Point Clearing-South Edge (Shade Edge 6d) and Comparison With the Air Temperature and Relative Humidity In the Observation Shed (70 cm) As Well As the Total Radiation.

During the nights of September 4th to 5th and 5th to 6th, in each case a sudden increase of soil surface temperature occurred when the air humidity at 70 cm above ground approximated values of 100%. As Hoffmann

stated, for dew formation a condition of total saturation must exist in the immediate vicinity of the deposit surface [11]; considering the temperature differences between air temperature (70 cm) and soil temperature (0 to 1 cm), this was the case. Since these sudden temperature increases could not be explained by the prevailing cloud, wind and radiation relationships, they must in each instance be explained as resulting from freed condensation heat from dew formation. The degree of the determined temperature increase is naturally dependent on the horizon limitation of the observation point and may reach several degrees (Table 6 and Figure 7). For the sake of clarity these dew-caused temperature increases have been shaded in. Because of a brief increase of total radiation on September 6th 1953 at approximately 0800, the total temperature increase at the soil surface by 7.7°C at this moment cannot be ascribed to dew formation. A measurement of the amount of dew was not effected but the vegetation and soil surface were wet until late morning. Since the wetting substantially reduced transpiration at least, this point of view may assume some significance for the precipitation-poor continental areas.

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